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DOUBLE QUARTER WAVE DEFLECTOR CAVITY DESIGN & SIMULATION

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Abstract

A Double Quarter Wave (DQW) Cavity has been designed, tested and installed for use in longitudinal measurements as part of a diagnostic beamline. This report will describe the design and testing used to characterize this cavity before its use in the study of a magnetized electron beam.

INTRODUCTION

The design process starts by specifying the desired performance of the cavity. In this case a zero-crossing-angle, low power deflection of a bunched electron beam operating at a frequency of 499 MHz. Other parameters such as tunability and adjustment for coupling were chosen to be optimized in the overall design.

Being a narrowband cavity ±1 MHz, it must be possible to tune the cavity resonance frequency to the operation frequency. This sensitivity of the resonance frequency requires a tuner to compensate for effects from unavoidable construction tolerances, temperature and pressure variations.

The copper cavity is expected to have power loss in the cavity wall, but low power requirements make this a minimal concern. Where Q_0 denotes the unloaded Q, resulting from just the wall losses, typical Q_0 values obtained in normal-conducting vacuum cavities made of Cu are 10^3-10^6, depending on geometry, size and frequency. The power 'lost' through the main power coupler is called the external Q_e. Since the power lost due to these different loss mechanisms must be added, the total resulting Q, also referred to as Q_l (the loaded Q), is calculated from Eq. 1 or 2 where β is the coupling factor.

$$1/Q_l = 1/Q_0 + 1/Q_e \tag{1}$$

$$Q_l = Q_0/(1+\beta) \tag{2}$$

In the process of designing this cavity we are therefore interested in simulation and measuring the operational frequency, tunablity, power and coupling. We have performed beam-dynamics simulations for the cavity itself, operation in the intended beamline and performed physical measurements of the cavities characteristic to compare with simulation.

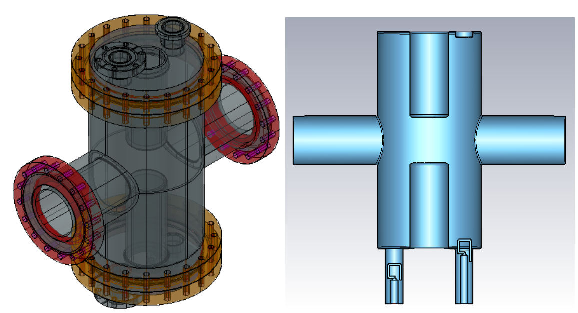
Finally the cavity was installed in the beamline and checked for functinality.

RF DESIGN OF THE CAVITY

The cavity delivers 8 kV for the required deflecting angle at f=499 MHz and is realized by a normal conducting DQW resonator. The design was done using CST-MWS simulation [1] and resulting Figures of merit for the cavity is listed in Table 1. The deflecting kick in the DQWR is a Lorentz force provided by TEM (fundamental) mode, whose main contribution comes from the electric field rather than the magnetic field. With z and y axis aligned with the beam axis and the vertical axis of the DQWR respectively, the force in the kick direction (y axis) is given as:

$$F_y = e(E_y + v_z B_x), \tag{3}$$

where e is electron charge and v_z is the velocity of an electron along the beam axis and is assumed to be speed of light. A 3D model of the cavity, a cut-away image of the cvaity, and 1D profile of the on axis E field are shown in Figs. 1a, 1b, and 2 respectively. Due to its vertical symmetry, the kick of the DQWR does not have large quadrupole fields in its profile.



(a) 3D Transparent model of cavity

(b) The internal structure of the DQWR

Figure 1: The structure of the DQWR

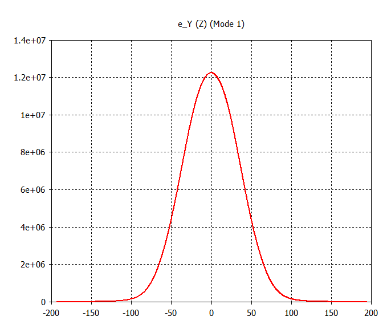


Figure 2: The Efield on-axis profile.

The cavity is equipped with a plunger-type tuner and a loop power coupler. A stub of the tuner is inserted to the

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"default" position to allow for bi-directional (±) tuning. this nominal position is 10 mm into the cavity. The tuning range and sensitivity is listed in Table 1. A loop coupler is to adjust the RF coupling after installation into the cavity by rotating the loop. The simulated angular profile of the coupling is shown in Fig. 3. In Fig. 3, β becomes maximum of 1.3 at $\theta = 180°$, from which one adjust down to critical coupling of $\beta = 1$.

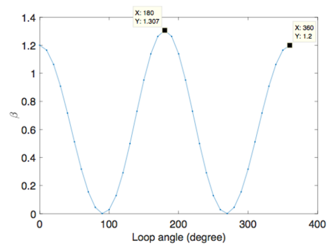

Figure 3: The angular profile of the coupling.

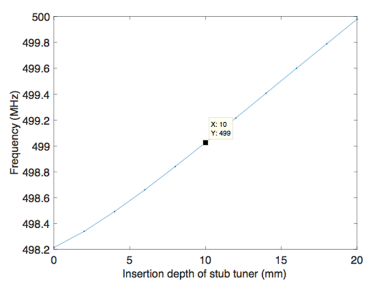

Figure 4: The tuning range and sensitivity of the tuner.

In Fig. 4, simulation results for tuning range is shown. One can see that below 2 mm linearity degrades due to radius of curvature that blends the connection where the coupler ports meet the cavity wall. The tuning and RF coupling control is achieved straightforwardly, i.e., frequency deviation as the loop rotates (by about ±25°) for the coupling adjustment is only 40 kHz, which can be easily compensated by moving the stubs up to ±0.25 mm.

Table 1: The Figures of Merit of the DQWR

Parameters	Unit	Value
Frequency f	MHz	499
Tuning sensitivity θ	kHz/mm	95
Tuning range	MHz	±0.95
RF coupling β	-	1
Dissipated power P_{wall}	W	25
Quality factor Q_0	10722	

DQW OPERATION IN SIMULATION

To simulate the operation of the cavity within the diagnostic beamline, the cavity field profiles are exported from CST as a 3D $Re[E]$ and $Im[H]$ fields. They are used in General Particle Tracer (GPT) software to simulate its operation. Within the GPT simulation a scaling factor is applied to these fields to give the necessary kick to the bunch. H is converted to B by the factor μ_0 and the only values extracted from GPT is longitudinal β_z and the aforementioned scaling factor. In this case, β_z refers to the bunch velocity proportionality to the speed of light. The wave number k for the RF is given by $\frac{2\pi}{\lambda}$. These values are all used in the calculation for the kick voltage applied to the bunch [2,3].

$$V_\perp = \int_{-\infty}^{\infty} \frac{E_\perp}{\beta_z} e^{\frac{ikz}{\beta_z}} - icB_\perp e^{\frac{ikz}{\beta_z}} dz \tag{4}$$

$k \approx 10.45$, $E_\perp = E_y(z)$, $B_\perp = B_x(z)$, $\beta_z = 0.595$, scaling factor from GPT simulation: $S = 0.007$. yeilding $V_\perp = 1.36$ MV.

Therefore, applying the scaling factor, the final operational kick voltage is 9.5 kV.

Moreover, the required power is proportional to the field squared. Therefore, the power loss calculated in CST as 289 kW times the scaling factor squared gives the lower bounds for power required to operate the cavity; calculated to be 14.1 W. However, the measured Q of the cavity is roughly 20% below CST simulation. Which means the power can be expected to be increased by 20% giving a new lower bound of 16.92 W.

BENCH TEST MEASUREMENTS

An accurate frequency for the cavity is a high priority and bench test measurements were done to test the frequency, tuning-range, coupling and electric center of the cavity. The two methods of measurement were simple readings from a network analyzer to measure frequency throughout the tuning-range via the coupling ports and then a standard wire stretch measurement which again measures resonant frequency, but primarily was used to find the electric center of the cavity.

The mechanical design was intentionally made with inner conductors to have excess material so they could be machined down precisely after initial measurements. After machining down the conductors to the precise length required, the cavity matched the designed 499 MHz. The tunabilty form the mechanical tuning stub with a travel of ±10 mm form a nominal position allowed for frequency ranges from 497.6-500.9 MHz. Realizing the desired tunability of ~ ±1 MHz.

Performing the wire stretch confirmed the electric center of the cavity was within 0.69 mm of the mechanical center. This is sufficiently close to consider on axis for our purposes. Measurements from the wire stretch are shown in Fig. 5. Off center, the cavity frequency can be seen at the designed 499 MHz and when on center the wire does not excite any modes, resulting in the graph in Fig. 5b.

When rotating the coupler and pick-up probe while monitoring the Q values from the network analyzer, it was found that critical coupling does occur in the orientations predicted

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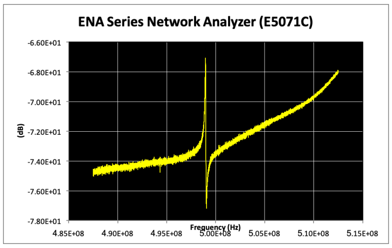
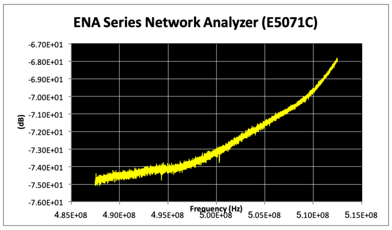


(a) Off-Center



(b) Center

Figure 5: Wire stretch measurement

and discussed in section 2. However, the Q_0 was found to be ~18% lower than the simulation predicted. This will not greatly effect operation as the power requirements are so low. The losses will simply be compensated by supplying more power to achieve the desired kick voltage.

INSTALLATION AND FUNCTIONALITY

The cavity was successfully installed in a diagnostic beamline as shown in Fig. 6. To minimize outgassing during operation, the cavity was heated to 150 C for 24 hours. The cavity was then powered to 200+ watts (far above operational requirements) through a range of frequencies to process out any field emissions.

The cavity's deflection was tested with a short bunch length which would requiring a higher power level than the design. Regardless, the cavity was able to show some zero-crossing-angle deflection of the bunch.

Stability of the cavity staying in tune was a concern so thermal images like the one seen in Fig. 7 were taken of the cavity while powered to monitor the increase in temperature and its relation to the tuning of the cavity.

The low power requirements ensures the temperature remains low and does not require any thermal stabilization. Operationally the cavity will be tuned so that the frequency will drift into the design resonance frequency at the cavities operating temperature.

CONCLUSION

The measurements made on the manufactured cavity closely match the design parameters and predicted performances of tunabilty. The Q was lower than expected from the simple values used in simulations based on copper being the material used for the cavity, but even with low Q the power requirements are still low for effective operation.

Figure 6: Cavity installed in beamline

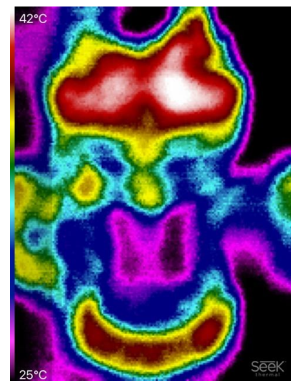


Figure 7: Thermal image

Installation and confirmation of effective use imply encouraging results that indicated the cavity is close to idealized conditions for its intended use in the diagnostic beamline. The future work related to this cavity is a the intended measurement in the beamline as all other development and testing has been completed.

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